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Extending the Motion Ranges of Magnetic Levitation for Haptic Interaction

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ABSTRACT

We have developed two different magnetic levitation devices which provide unprecedented ranges of motion in both translation and rotation to a levitated handle to be used for tool-based haptic interaction. The first device levitates a handle attached to a thin spherical shell of flat coils suspended in permanent magnet fields using Lorentz forces. A novel coil type and magnet configuration provides motion ranges of 50 mm and 60 degrees in all directions, double the translation and triple the rotation ranges of the current maximum range Lorentz levitation haptic devices developed at Carnegie Mellon University.

The second device uses a planar array of cylindrical coils to levitate a platform of one or more magnets. By using redundant control methods and an experimentally measured high resolution model of the forces and torques generated on the levitated magnets from each coil, the translation range of the magnet in horizontal directions and its rotation in all directions and can be extended potentially indefinitely. The present prototype uses 10 coils to levitate a single magnet over a 80x60 mm planar range, a 30 mm vertical range, and a tilt range of 40 degrees, or to control the yaw rotation of a pair of magnets over 360 degrees. Design and control methods are presented with preliminary motion trajectory results from both devices.

1 INTRODUCTION

Magnetic levitation has many general advantages compared to motorized linkages when applied as a means of actuation for six degree-of-freedom haptic interaction with simulated environments through a grasped tool handle: The simple dynamics of a single moving lightweight rigid-body part with no friction or backlash, coupled with high-resolution optical position sensing and a high-frequency, stiff feedback control system, results in a very high performance haptic interaction device in terms of its controlled position and force bandwidth and resolution, and its impedance range and maximum stiffness.

The major disadvantage of magnetic levitation systems for haptic interaction has been their limited motion ranges in most or all degrees of freedom, due to a combination of narrow magnetic field gaps and linearized magnetic actuation models which are only valid in a neighborhood of a given setpoint. As a result, magnetic levitation haptic interfaces which have been developed to date focus on fingertip-scale motions, and provide variable indexing, rate control, and scaling methods through software to simulate interaction with larger environments.

We are developing two magnetic levitation systems which can be used as haptic interaction devices, providing motion ranges many times those of current magnetic levitation haptic devices. These new devices aim to provide haptic interaction on the scale of hand, wrist, and forearm motions rather than fingertip motions only. The larger motion ranges enable life-sized haptic simulations of many more typical tasks using tools grasped in the hand such as turning keys and doorknobs, manipulating a screwdriver or socket wrench, and many surgical tasks such as suturing and intubation.

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1.1 Magnetic Levitation Feedback Control

Magnetic levitation devices require closed-loop feedback control for stable operation, aside from exceptional cases involving diamagnetic effects or spin stabilization. If realtime position and orientation sensing is available and a model of the transformation between electromagnetic coil currents and the force and torque vectors generated on the levitated body is known, then proportional and derivative gain feedback at a 1000 Hz control rate with a constant feedforward gravity cancellation is typically sufficient for stable levitation and realistic haptic interaction with simulated environments, in which the stiffness and damping of solid contacts between a simulated tool and objects in the virtual environment are equivalent to the feedback control proportional and derivative gains, for example.

The transformation between coil currents and generated force and torque vectors can be represented by the matrix relation $\mathbf{F} = \mathbf{AI}$, where :

$$\mathbf{F} = \begin{bmatrix} f_x \\ f_y \\ f_z \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix}, \text{ and } \mathbf{I} = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \\ i_6 \end{bmatrix}. \tag{1}$$

If the transformation matrix $\mathbf{A}$ can be calculated and is invertible for any position and orientation throughout the motion range of the levitated body, and the resulting currents $I = A^{-1}F$ for the required levitation and interaction can be generated by the amplifiers and do not overheat the coils, then the system can be successfully levitated and provide haptic feedback.

In our two magnetic levitation systems, real time long-range position feedback is provided at 1000 Hz by a 0.01 mm resolution optical position sensor [1] mounted to a rigid frame 1.6 m above the table. This position sensor detects the positions of a defined set of strobing infrared LED markers fixed to a single rigid body and calculates the spatial position and orientation of the body. Coil currents are generated by an array of current amplifiers[2] controlled by analog signals generated by a 1000 Hz control system executing on a PC.

2 RESEARCH BACKGROUND

Previous magnetic levitation devices developed for force-reflecting teleoperation and haptic interaction, and similar previous to our work in this paper are described below.

2.1 Magnetic Levitation Haptic Interaction

Hollis and Salcudean pioneered the use of Lorentz force actuation from currents in flat racetrack-shaped coils suspended between

[1]Optotrak, Northern Digital Inc.
[2]Copley Controls

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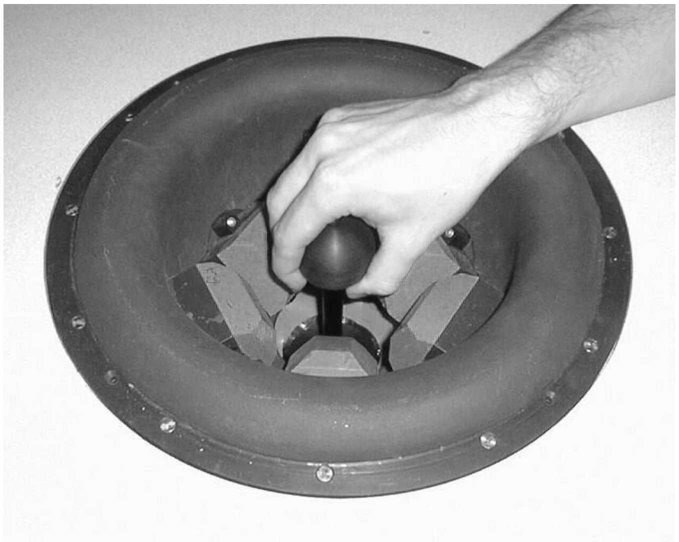

Figure 1: Interaction with Carnegie Mellon Lorentz magnetic levitation haptic interface

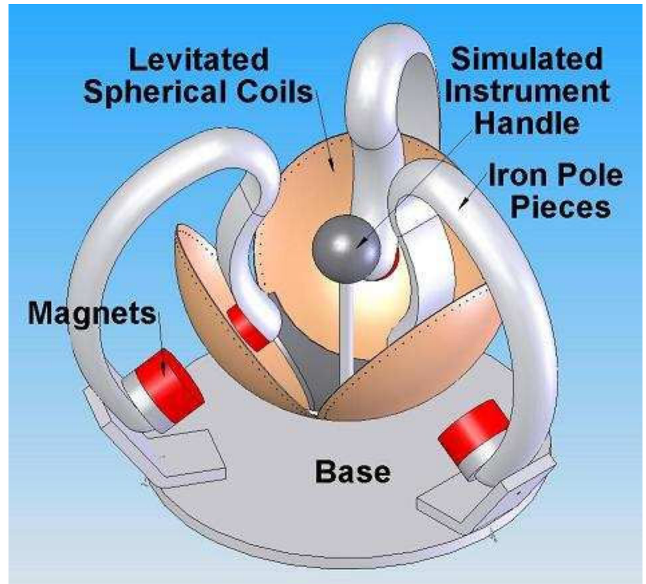

Figure 2: Extended range Lorentz levitation device design

horseshoe-shaped magnet assemblies [7]. Devices developed using Lorentz levitation technology include the IBM magic wrist [6] for fine positioning and compliant assembly, the teleoperation master [14] and *powermouse* [13] from the University of British Columbia, the hemispherical maglev haptic [3] interface developed by Berkelman at Carnegie Mellon and shown in Fig. 1, and an improved hemispherical magnetic levitation haptic interface which is in commercial production[3]. These devices have provided excellent performance in terms of control bandwidths, position resolution, and impedance ranges, but their range of motion is limited to 30 mm and 20 degrees or less in all directions due to the limited areas of the actuator coils and magnetic field gaps.

2.2 Coil Array Levitation for Haptic Interaction

A limited number of systems have been developed to provide large ranges of motion for levitated magnets using arrays of cylindrical coils by electromagnetic attraction and repulsion. Groom *et al* from NASA Langley performed extensive analysis of electromagnetic actuation and feedback control methods for levitation of cylindrical magnets by a set of cylindrical coils for large angular motion capabilities, however the implementation was limited to large large coils and much smaller magnets and motion ranges over which the magnetic fields could be approximated to constant [5]. Our approach differs from this prior work in that the actuation forces and torques over the magnetic field of an individual coil are measured experimentally, so that any variations in the magnetic properties and dimensions of the coils and magnets are accounted for in the actuation model, and as a result magnets can be levitated and moved over distances many times larger than the dimensions of the individual coils and magnets.

Lai, Lee, and Yen [9] have also developed a planar levitation system with a small range of motion using an array of coils and several magnets to stabilize all axes of translation and rotation. Khamesee and Shameli have developed a magnetic levitation system which can suspend a small magnet and control its position within a volume many times larger than the magnet size [8] however the magnet orientation is not controlled.

The development of spherical motors by Lee [15] and Chirikjian [4] is based on similar methods, but the moving parts are not levitated translation is not controlled. Our planar system, to be described below, controls both translation over several times the dimensions of the levitated body, and rotations of 40 degrees or more together.

[3]Butterfly Haptic LLC

3 Extended Range Spherical Lorentz Levitation Haptic Interface

Our first extended range magnetic levitation design is a Lorentz levitation device with coils on a spherical shell and a user handle mounted at the center of the shell, as in the Carnegie Mellon Lorentz devices. Our device uses a novel coil shape, magnet configuration, and arranges the coils in two layers so that the magnetic field gap widths can be doubled at approximately the same field intensity as before and the coil areas can be increased many times more on a shell of approximately the same radius, resulting in a doubling of the translation range and a tripling of the rotation range in all directions.

3.1 Design

The basic design is described in more detail in [1] and shown in Fig. 2. Instead of using racetrack-shaped coils in which the coil windings follow oval paths, a new coil shape is used in which the windings follow straight paths across the centers of the coils, and curved return paths around the periphery of the round coils. This allows the coils to be arranged in two layers, with the straight wires across the centers of the coils orthogonal to one another. In this arrangement, the areas of the coils can be increased considerably without increasing the radius of the spherical shell, and each pair of layered coils requires only two magnets to generate their shared magnetic field. Large, curved iron pole pieces pass above and around the levitated coil assemblies to form a magnetic flux path from one magnet to the other on the opposite sides of each gap.

The centers of the coil pairs are arranged at 0, 120, and 240 degrees around the circumference at an angle of 35 degrees below the horizontal plane, on a spherical surface with a 125 mm radius, and each coil spans a solid angle of 90 degrees. The effective solid angle of each coil is reduced to approximately 70 degrees due to the width of the magnets and the return paths of the wires around the edges of the coils and the magnet gaps are 53 mm, so that the device can provide a motion range of 50 mm in translation and approximately 60 degrees in rotation in all directions.

As the translation range is approximately double and the rotation range is triple that of previous levitated haptic interaction devices, the workspace volume is actually increased by a factor of 8 and the rotation space by a factor of 27. The increased motion range of the new device is not merely an incremental improvement, but enables a qualitatively much greater variety of interactive tasks to be simulated as the increased range is comparable to the full range of human wrist movement, whereas previous haptic levitation devices could accommodate fingertip motions only. For example, common manual manipulation tasks such as turning doorknobs, keys, and hexagonal nuts and screwheads can be realistically haptically simulated with the new device, and 60 degrees of rotation and 50 mm of translation is sufficient to simulate many tasks in minimally invasive surgery [12].

The force generated by each coil can be modelled as a single force vector at the center of each coil, and one coil in each pair generates vertical and the other generates horizontal forces. The magnitude of the force generated by each coil is approximately 3.0 Newtons/Amp. With the coil center locations at:

$$\mathbf{r}_{1,2} = 0.125 \begin{bmatrix} cos(35) \\ 0 \\ -sin(35) \end{bmatrix}, \; \mathbf{r}_{3,4} = 0.125 \begin{bmatrix} cos(120)cos(35) \\ sin(120)cos(35) \\ -sin(35) \end{bmatrix}, \quad \mathbf{r}_{5,6} = 0.125 \begin{bmatrix} cos(240)cos(35) \\ sin(240)cos(35) \\ -sin(35) \end{bmatrix}, \tag{2}$$

in m, and the forces generated by each coil at:

$$\mathbf{f_1} = 3.0 \begin{bmatrix} sin(35) \\ 0 \\ cos(35) \end{bmatrix} i_1, \; \mathbf{f_2} = 3.0 \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} i_2,$$
$$\mathbf{f_3} = 3.0 \begin{bmatrix} cos(120)sin(35) \\ sin(120)sin(35) \\ cos(a35) \end{bmatrix} i_3, \; \mathbf{f_4} = 3.0 \begin{bmatrix} -sin(120) \\ cos(120) \\ 0 \end{bmatrix} i_4,$$
$$\mathbf{f_5} = 3.0 \begin{bmatrix} cos(240)sin(35) \\ sin(240)sin(35) \\ cos(35) \end{bmatrix} i_5, \; \mathbf{f_6} = 3.0 \begin{bmatrix} -sin(240) \\ cos(240) \\ 0 \end{bmatrix} i_6, \tag{3}$$

in N, then the current to force and torque vector transformation matrix can be given as:

$$\begin{bmatrix} f_x \\ f_y \\ f_z \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} \mathbf{f_1} & \mathbf{f_2} & \cdots \\ \mathbf{r_1} \times \mathbf{f_1} & \mathbf{r_2} \times \mathbf{f_2} & \cdots \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \\ i_6 \end{bmatrix}. \tag{4}$$

to relate currents in A to forces in N and torques in N-m. When the sphere radius and the force magnitudes are normalized to 1 to compensate for differences in force and torque units, the condition number of the transformation matrix is 3.7, indicating that the matrix is invertable and forces and torques can be efficiently generated in all directions without requiring excessively larger coil currents for some directions.

3.2 Analysis and Fabrication

Electromagnetic finite element analysis[4] was performed to find magnet shapes and dimensions to concentrate and maximize magnetic fields necessary for levitation. The basic result of the magnetic field acting on the coils in between the magnets is shown in Fig. 3, which was obtained from a 3D finite element analysis using cylindrical N50 neodymium-iron-boron magnets and a pole piece of pure iron with a flux return path of 450 mm in circumference outside of the frame of the figure shown. This analysis indicated that the minimum field strength in between magnets is approximately 0.25 T, which is expected from experience [3] to be sufficient for levitation and high-fidelity haptic interaction. The mass of the fabricated levitated body is 1200 g; by fabricating new coils using aluminum wire and using a more lightweight support structure we aim to reduce the levitated mass to 500 g or less.

[4]Ansys Emag

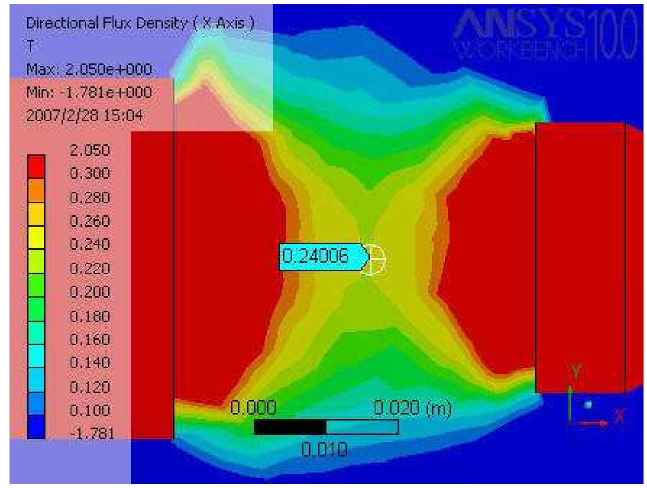

Figure 3: Spherical Lorentz levitation device magnetic field finite element analysis

The fabricated device is shown in Fig. 4. In the pictured figure, the iron pole pieces on two of the magnet assemblies have been rotated about the magnet axes by approximately 30 degrees to provide more ergonomic access for the user to more easily grasp the levitated handle without affecting the magnetic fields or the range of motion of the device.

3.3 Results and Discussion

A sample large scale vertical step input motion trajectory for the free-floating levitated coils in the vertical direction is shown in Fig. 5. The control gains used were as follows:

	translation	rotation
K_p	2.0 N/mm	0.0875 N-m/degree
K_d	0.01 N-sec/mm	0.00035 N-m-sec/degree

As these are very preliminary results, it is expected that more careful modeling, calibration, and signal processing will result in considerable increases of the maximum stable gains and a more damped response.

Regarding the positioning accuracy of the levitated bowl and the stiffness of the coil structure, it is notable that any flexion of the coils from high actuation forces would not affect the position accuracy of the manipulation handle, as the position sensing feedback is from LED markers close to the center of the structure, which is reinforced with an additional layer of aluminum and a collar around the base of the handle. Furthermore, for haptic interaction applications, absolute position accuracy of the device is not as critical as the incremental position and force accuracy and control bandwidths to the perceived fidelity of the haptic interaction.

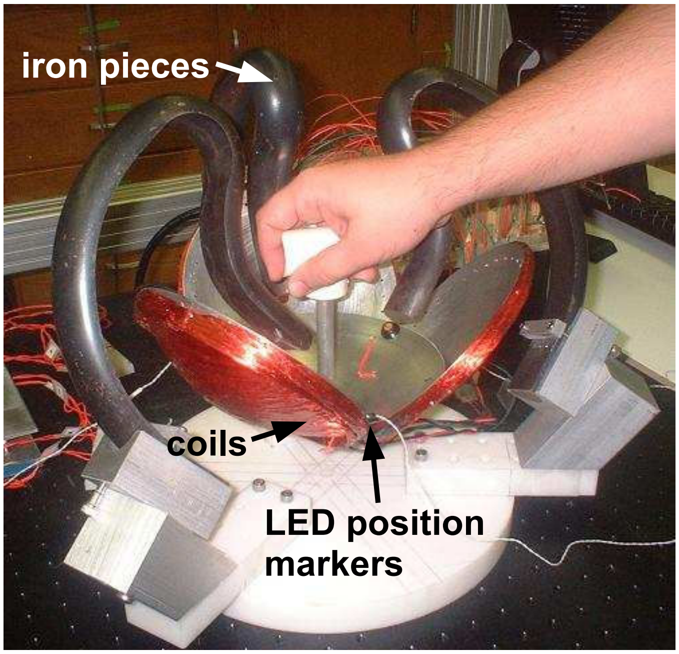

Figure 4: Fabricated extended range Lorentz levitation device

4 Planar Array Magnetic Levitation Haptic Interface

A redundant actuation method was used to levitate the magnet by combining actuation forces and torques from more than 5 coils at a time. The potential advantages of redundant actuation compared to selections of coil subsets at each magnet position are that the maximum required coil currents for levitation may be reduced by distributing the generation of lifting forces over more coils, and discontinuous force disturbances due to measurement and position errors as coil currents are abruptly switched on and off during motion trajectories can be avoided. Ten coils of 25 mm diameter, 30 mm height, and 1000 windings are currently used, providing a motion range of 60x80x30 mm with a tilt range of 40 degrees. Yaw rotation cannot be controlled with a single disk magnet due to its radial symmetry, so single magnet platform levitation leaves the yaw angle uncontrolled. The array levitation control methods, design, and initial results are described in further detail [2].

A standard computer mouse shell has been adapted as a levitated handle to provide haptic force and torque feedback, shown in Fig. 6. The levitated mass is approximately 125 g.

4.1 Control

To determine the model of force and torque generation between a single magnet and coil, an experimental setup of motion stages and a force sensor was used as in Fig. 7. Although it is possible to obtain a force and torque generation model either analytically (as described in [5]) or from electromagnetic finite element analysis, in this case it is simpler and faster to obtain the model experimentally, and furthermore the effects of variations in the magnet material and its magnetization are accounted for directly.

The radial force u, vertical force v, and tilting torque w generated between the magnet and coil were recorded at 1 mm intervals of vertical and radial separation, resulting in the force and torque model shown in shown in Fig. 8. The forces and torques generated by each coil were found to be independent and proportional to each coil current to a very close approximation, allowing the current to force and torque transformation to be represented in linear matrix form at any magnet position and orientation. This data was used to

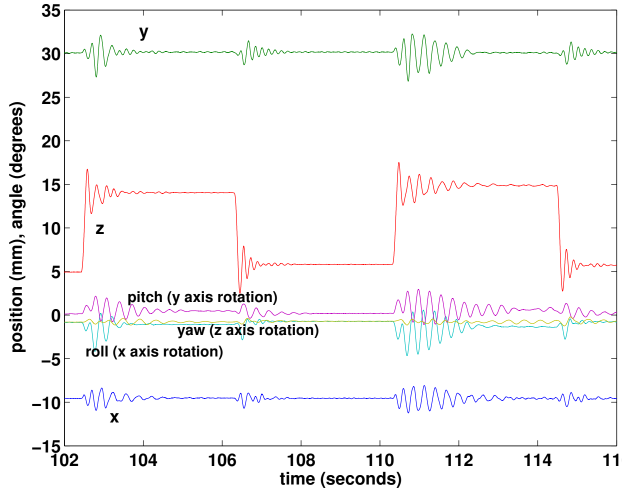

Figure 5: Spherical Lorentz levitation device motion trajectory

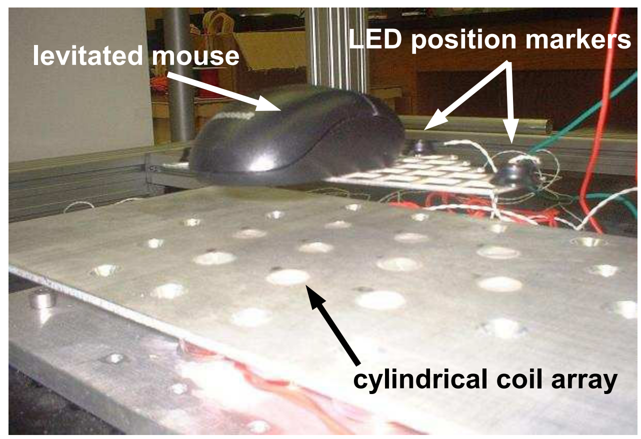

Figure 6: Computer mouse levitated above coil array

calculate the current to force and torque transformation for 5 degree of freedom single magnet levitation as follows:

$$\begin{bmatrix} f_x \\ f_y \\ f_z \\ \tau_x \\ \tau_y \end{bmatrix} = \begin{bmatrix} \cos(\theta_1)u(r_1,m_z) & \cos(\theta_2)u(r_2,m_z) & \cdots \\ \sin(\theta_1)u(r_1,m_z) & \sin(\theta_2)u(r_2,m_z) & \cdots \\ v(r_1,m_z) & v(r_2,m_z) & \cdots \\ -\sin(\theta_1)w(r_1,m_z) & -\sin(\theta_2)w(r_2,m_z) & \cdots \\ \cos(\theta_1)w(r_1,m_z) & \cos(\theta_2)w(r_2,m_z) & \cdots \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ \cdots \end{bmatrix} \tag{5}$$

where r_i and θ_i are the magnitude and angle of the vectors from each coil center to the magnet center projected onto the horizontal plane, and m_z is the vertical position of the magnet. For 6 degree of freedom controlled levitation of platforms with multiple disk magnets, additional terms must be added due to the $\mathbf{r} \times \mathbf{f}$ torques from magnet forces $\mathbf{f}$ generated at a distance $\mathbf{r}$ from the center of mass of the levitated platform; it is these transformation terms which enable generation of $\tau_\mathbf{z}$ torques to control the yaw angle.

The Moore-Penrose pseudoinverse [10, 11] of the matrix transformation was used to find the least square sum of currents for force and torque generation for levitation control. Condition numbers of the transformation matrix across the motion plane are shown in Fig. 9 for a 20 mm levitation height. The locations of the 10 coil centers are indicated by asterisks '*', these are arranged in a hexagonal configuration with a spacing of 35 mm. The transformation con-

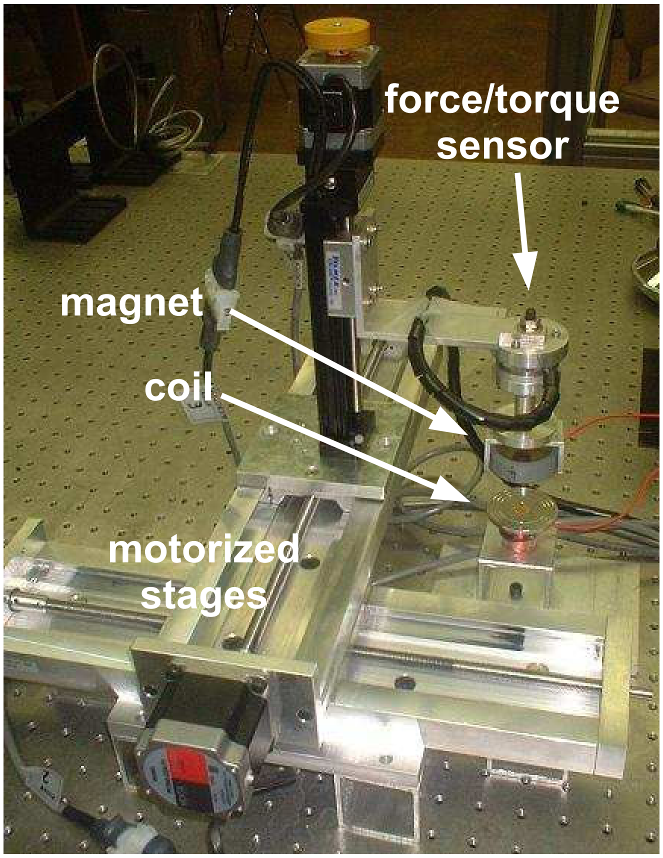

Figure 7: Electromagnetic force and torque measurement setup for planar array levitation

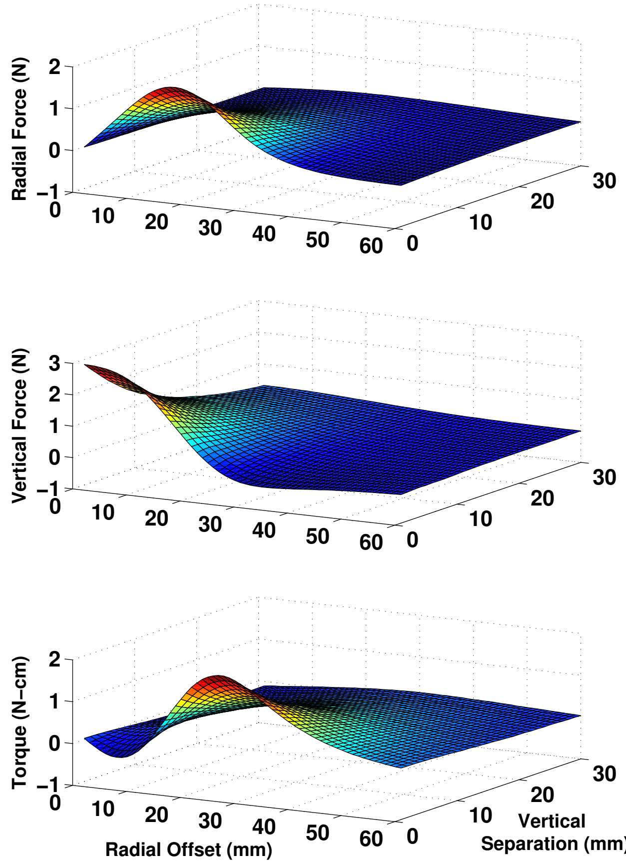

Figure 8: Planar array magnetic force and torque measurement data

dition numbers are greatest directly above the coil centers because the horizontal force and torque torque generation capabilites of the coil underneath are zero although the vertical force generation efficiencies are maximized at these locations.

4.2 Results and Discussion

A large scale motion trajectory from a single free-floating levitated magnet is shown in Fig. 10. The control gains used were as follows:

	translation	rotation
K_p	0.2 N/mm	5.25 N-mm/degree
K_d	0.002 N-sec/mm	0.0525 N-mm-sec/degree

The position control bandwidths of the system are limited by the maximum stable proportional gain, or stiffness of the controller, this gain is limited in turn by the resolution and noise level of the position sensor and the update rate of the controller.

Initial levitation of two magnet platforms has also been demonstrated for 6 degree-of-freedom levitation control including yaw rotations, as shown in Fig. 11.

5 Conclusion and Planned Work

The two described magnetic levitation systems each provide greater motion ranges than any other previous magnetic levitation device for haptic interaction. The planar array levitation system has greater potential for further expansion of its motion range in horizontal directions and rotations in all directions, but it is less efficient than the Lorentz levitation device, which can generated higher forces and torques without overheating. Each of the two systems will be interfaced to publically available haptic interaction software such as *Chai3d* and *H3D* to evaluate user perception and task performance using the devices.

Further development to be undertaken for each system includes modeling of the magnetic field variations in the Lorentz force device for better control performance, and modeling of magnetic actuation at greater rotation angles for the planar system, potentially reaching 360 degrees of rotation in all directions with additional LED position markers on all sides of the magnet platforms. The planar system will be expanded to 16 coils or more for a larger planar motion range, and coils with iron cores will be used for more efficient actuation.

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References

[1] P. Berkelman. A novel coil configuration to extend the motion range of lorentz force magnetic levitation devices for haptic interaction. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, San Diego, October 2007.

[2] P. Berkelman and M. Dzadovsky. Magnet levitation and trajectory following motion control using a planar array of cylindrical coils. In

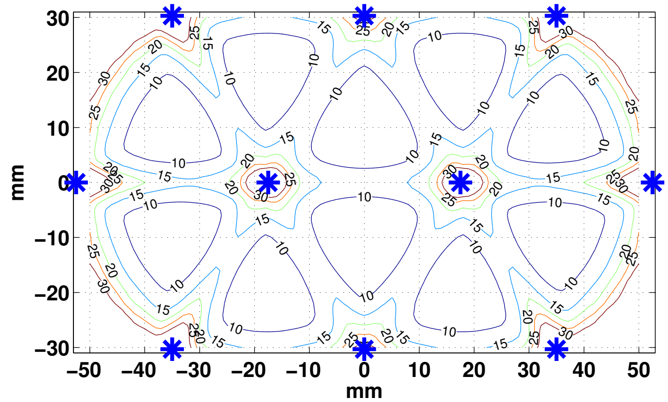

Figure 9: Planar array current to force-torque transformation condition numbers at a 20 mm levitation height, with coil centers as indicated by asterisks

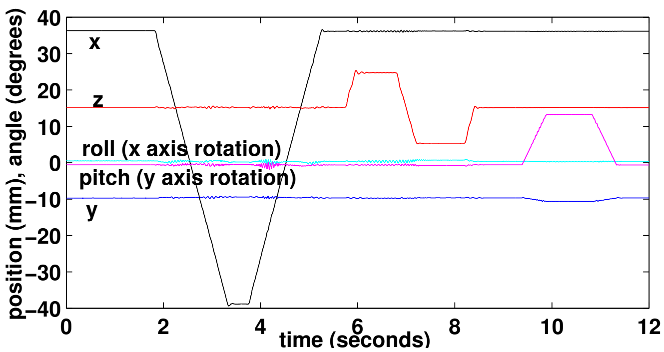

Figure 10: Planar array trajectory plot

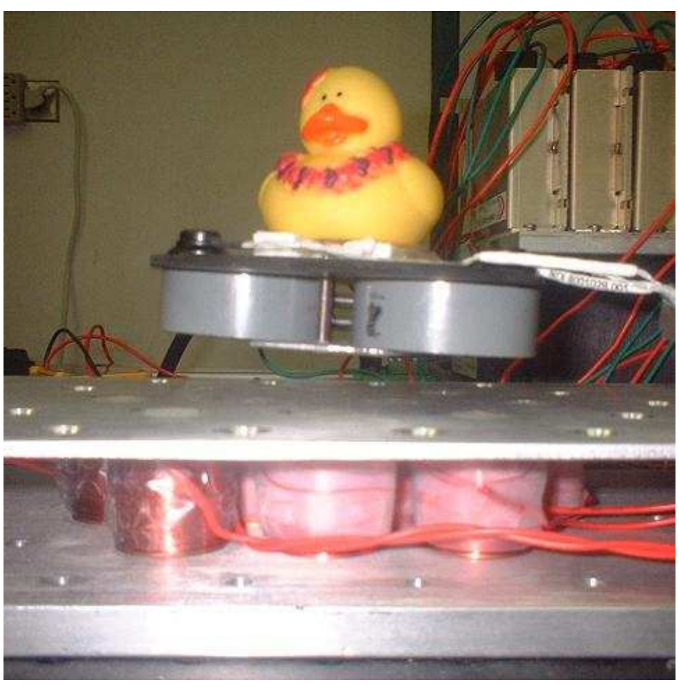

Figure 11: Two disk magnet levitation for 6 DOF levitation control

ASME Dynamic Systems and Control Conference, Ann Arbor, October 2008.

[3] P. J. Berkelman and R. L. Hollis. Lorentz magnetic levitation for haptic interaction: Device design, function, and integration with simulated environments. *International Journal of Robotics Research*, 9(7):644–667, 2000.

[4] G. S. Chirikjian and D. Stein. Kinematic design and commutation of a spherical stepper motor. *IEEE/ASME Transactions on Mechatronics*, 4(4):342–353, December 1999.

[5] N. J. Groom and C. P. Britcher. A description of a laboratory model magnetic suspension testfixture with large angular capability. In *IEEE Conference on Control Applications*, pages 454–459, Dayton, September 1992.

[6] R. L. Hollis, S. Salcudean, and A. P. Allan. A six degree-of-freedom magnetically levitated variable compliance fine motion wrist: design, modeling, and control. *IEEE Transactions on Robotics and Automation*, 7(3):320–332, June 1991.

[7] R. L. Hollis and S. E. Salcudean. Lorentz levitation technology: a new approach to fine motion robotics, teleoperation, haptic interfaces, and vibration isolation. In *Proc. 6th Int'l Symposium on Robotics Research*, Hidden Valley, PA, October 2-5 1993.

[8] M. B. Khamesee and E. Shameli. Regulation technique for a large gap magnetic field for 3d non-contact manipulation. *Mechatronics*, 15:1073–1087, 2005.

[9] Y.-C. Lai, Y.-L. Lee, and J.-Y. Yen. Design and servo control of a single-deck planar maglev stage. *IEEE Transactions on Magnetics*, 43(6):2600–2602, June 2007.

[10] E. H. Moore. On the reciprocal of the general algebraic matrix. *Bulletin of the American Mathematical Society*, 26:394–395, 1920.

[11] R. Penrose. A generalized inverse for matrices. *Proceedings of the Cambridge Philosophical Society*, 51:406–413, 1955.

[12] J. Rosen, J. D. Brown, L. Chang, M. Barreca, M. Sinanan, and B. Hanaford. The blue DRAGON - a system for measuring the kinematics and the dynamics of minimally invasive surgical tools invivo. In *IEEE International Conference on Robotics and Automation*, Washington DC, May 2002.

[13] S. Salcudean and N. Parker. 6-dof desk-top voice-coil joystick. In *International Mechanical Engineering Congress and Exposition*, Dallas, November 1997.

[14] S. Salcudean and T. Vlaar. On the emulation of stiff walls and static friction with a magnetically levitated input-output device. In *ASME IMECE*, pages 303–309, Chicago, November 1994.

[15] L. Yan, I.-M. Chen, C. K. Lim, G. Yang, W. Lin, and K.-M. Lee. Torque modeling of spherical actuators with double-layer poles. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 5447–5452, Beijing, October 2006.